Instrumentation

I Introduction (logistic, homework, goal of this class)

II Challenges

III Different detectors for different purposes

- **1 Imaging**
- **2 Spectral analysis**
- **3 (Timing)**

IV Current and future missions

- **1 Chandra and XMM-Newton**
- **2 Future missions**

Homework

This will be the homework for both classes on instrumentation. Chose one of your favorite object (stars, neutron stars, CVs, SNRs, black holes, galaxies, cluster of galaxies...) and investigate what would be the best (existing, past or planed) instrument to observe it. Describe the characteristics of the instrument and explain why this would be the best choice for the object (or the category of object) you chose.

Due date: February 1st– 4 typed pages maximum. –

Challenges

A) Space, space, space

- Light
- Not too expensive
- Robust and reliable
- Maintenance free??

High-energy photons are hard to focus or image for astronomical studies.
In the present state of instruments available, there is **not one** instrument which is **the best** but instead there are different detectors which all have different purposes.

For the moment, one can do imaging, timing, and spectroscopy with X-rays.

There are still no instruments capable of doing X-ray polarization or X-ray interferometry.

B) Why bother?

- Some wavelengths are not accessible if not in space
- No problems with atmosphere,...
- Different wavelengths indicates different astrophysical phenomena

The ideal X-ray detector has high spatial resolution with a large collecting area. Excellent temporal resolution and ability to handle large count rates. Perfect spectral resolution over a large energy range. It suffers no degradation in space and has almost no internal background. It is not susceptible to radiation damage. It is simple to operate, cheap to build and sturdy. It has a minimal power consumption and it is light in weight.

This is when I usually wake up....

This ideal detector does not exist- What we have are a number of different detectors which have only some of the above attributes.
All depends on what science you want to do.

- Imaging analysis?
- Spectral analysis?
- Timing analysis?

You'll chose the detector the most appropriate to your needs.

Problems and challenges of X-ray imaging studies

Imaging high energy photons is very difficult: with a standard design telescope, the photon would just pass through the mirror. Before one can detect X-ray for imaging purposes, one has to focus those X-ray on the detector. There are several techniques to do either that or just collect photons coming in with some spatial information.

- Light buckets
- One-dimensional imaging systems
- 2-d imaging

  1) Kirkpatrick-Baez grazing incidence optics
  2) Wolter type I (paraboloid/hyperboloid system)

The Microchannel plate

A microchannel plate is basically a array of tiny, tiny photomultipliers.

Microchannel plates were the best for imaging during the last decades.
They have been essentially overshadowed by CCDs (next week class).
A very good feature of MCPs is their timing resolution.
Microchannel plates are intrinsically fast devices and are used extensively for that.
The biggest problem with MCPs is their lack of energy response-

The proportional counter

The proportional counter is type of gas-filled detector.
The gas is usually a mixture of a large amount of inert gas (can be Argon, can be Xenon - can be both) and sometime either methane or carbon.
The incoming X-ray ionize some of the atoms in the chamber. The electrons and ions created by this incident radiation drift to their respective collecting electrodes. Because of their low mobility, nothing much happens with the ions. On the other hand, the electrons are easily accelerated by the existing field and gain significant kinetic energy.
If this energy is greater than the ionization energy of the neutral gas, it is possible to create a secondary ion-electron pairs. Then this secondary electron is also accelerated to ionization potential of the gas and triggers more and more collision.

This is known as the Townsend avalanche.

Under proper condition (depending on the voltage applied on the wires in the chamber) the number of secondary ionization events is proportional to the number of primary ions formed (proportional to the energy of the incoming photon).

A Position Sensitive Proportional Counter (PSPC) is a PC with position determination capabilities.
Based on the principle of charge division, the anode wire in a PSPC is fabricated so that the collected charge is divided between the the amplifiers at either end of the wire. The division is done in a proportion which is related to the position of the interaction.
A PSPC was flown on-board the ROSAT satellite launched in June 1990-

Problems and limitations of proportional counters

Because of slow diffusion, the gas in the detector has to be replenished- When this is not possible, the detector has a given (small) lifetime.
Because all the energy of the radiation has to be detected within the detector's enclosure, proportional counter for high energy photons have to be very large.
The spectral energy resolution is limited by the statistical fluctuations in the number of primary electrons created-

Basic principle

CCDs (Charge-Coupling Devices) are solid-state detectors. The simplest way of looking at photons interacting with a solid-state detector is to consider that the (electrons/ion) couple in a gas is replaced by an (electron/hole) couple in a solid (a hole is simply an electron vacancy in the valence band of the solid).

Before starting with CCDs (Charge-Coupling Devices), let's understand the principle of a p-n junction in semi-conductors.

The electrons in the conduction band diffuse across the junction, producing a potential difference. When the potential created is large enough to stop the electron diffusion, the diffusion stops. Incident light of sufficient energy on that junction can create electron-hole pairs in both sides of the junction. The electrons in the conduction band in the p-region are attracted to the n-region by the potential difference across the junction and will flow in that direction. The holes in the valence band of the p-type region are opposed by the potential and don't move. In the n-region, it is the inverse, the electrons do not move while the holes are pushed across the junction. Thus a current is generated by the incoming radiation.

CCDs

A CCD detector is an array of such p-n junctions (Metal-Oxide Semiconductor (MOS) capacitors)– Each junction is kept at a small positive voltage which is sufficient to drive the holes away from the thin layer between the electrode and the semiconductor. The electrons, on the other hand are attracted in the small region just beneath it. The electron-hole pairs produced in the depletion region by the incident radiation are separated out and the electrons accumulate in the storage region. The accumulated electron charge is a function of the intensity of the illuminating radiation.

CCDs

The incoming high-energy photons (energy E) have a large cross-section for interacting with the inner K and L shell of the silicon. There are N=E/w electron-hole pairs created – w is the average energy necessary to create a pair. w is a weak function of temperature and is around 3.6 eV for Silicon and around 10 times as many charge carriers are liberated by the absorption of a photon of energy E in a solid than in a counting gas.

Reading out CCDs

One of the characteristics of X-ray CCDs compared to CCDs used in optical astronomy (and were developed much earlier) is that they are "photon counting devices".

To read out this “electric” image, we use the method of charge coupling. The voltage applied “sweeps” though the array to get the charge moved from the detector area to what is called the “storage” area – then the charges are read out from that storage area.

Spectral and spatial resolution of CCDs

CCDs are both imaging and spectral detectors. Their spatial resolution is a combination of the quality of the X-ray telescope (and mirrors) and of the pixel size on the CCDs. Their spectral resolution varies as a function of many parameters and can be affected by many factors.

- Statistical

As in gas detector, there is an intrinsic limitation in the energy resolution of the detector due to the statistical fluctuations in the number N of electron-hole pairs (electron-ions pairs in the cases of gas detectors). The Fano factor, F, characterizes how big is this effect. $\sigma^2 = FN$
(pure poissonian (random) fluctuations would imply F=1). In case of gas detectors F ranges from $\sim$ 0.2 to 0.3, it is 0.1 for Si-based solid detectors.
These two effects combined (more pairs created with smaller statistical fluctuations) lead to a much better energy resolution for semiconductor detectors than gas detectors.

- Loss of charge during the transfer

During the sweep of charge across the CCDs, it is essential to minimize the losses– Some charges can become trapped in the silicon. This can happen because of defects in the crystalline structure, or it could be a defect introduced in the manufacturing process- Many factors can affect the amount of charge trapping: the temperature, previous history of charge passing through, ... Radiation damages to the CCD can induce problems for the spectral resolution (as seen with Chandra)-

- Signal from thermal electrons (Dark noise)

This why the CCDs are cooled (to minimize the contribution from the thermal excitation of the charge carriers).

Existing missions with CCDs

- ASCA 1993-2001
- Chandra 1999- (CTI problems)
- XMM-Newton 1999-

Using CCDs with other methods

- Transmission gratings on Chandra
- Reflection gratings on XMM-Newton

Problems with gratings

- Dispersive technology

Astro-E and then Astro-E2

Basics of X-ray calorimetry-

- Should operate at low temperature
- Absorber should be opaque to X-rays
- Absorber should have low heat capacity (small energy deposition translates to measurable temperature change
- Absorber must distribute the energy of the initial photon
- Sensitive thermometer
- Weak thermal link

Problems with calorimeter

- Life time limited by the low temperature constraint
- "Noise" due to random transfer of energy across the link
- White noise or Johnson noise is an electrical equivalent of the Brownian motion